Inclusion of Multiple Functional Types in an Automaton Model of Bioturbation and their Effects on Sediments Properties

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LONG-TERM GOALS

The long term goal is a quantitative and mechanistic understanding of the relationship between infaunal ecology and the consequent modification of sediments, including the creation and destruction of heterogeneities and the modes and rates of sediment component mixing.

OBJECTIVES

The development of an individual-based model (computer code) of sediments and organisms that utilizes biologically relevant parameters, such as animal sizes, population density, feeding and locomotion rates, and probabilities for observed behavior(s), to drive the model and produce predictions about sediment composition and fabric.

APPROACH

Biologically active sediment is represented on a computer as a regular lattice of quasi-particles with individually assigned chemical, biological or physical properties. Model benthic organisms are introduced in the form of automatons, i.e. programmable entities, that are capable of moving through the particle lattice by displacing or ingesting-defecating particles. Each automaton obeys a set of rules, both deterministic and stochastic, designed to mimic real organism behavior, with different types of organisms having different sets of rules. The acronym for the model is LABS (lattice-automaton bioturbation simulator).

This project involves myself, a post-doctoral fellow, Dr. Katherine Huang, and a Ph.D. graduate student, Daniel Reed. We also collaborate with Dr. Filip Meysman, a former PDF on this project, who is now at NIOO in the Netherlands and his supervisor, Dr. Jack Middelburg, of the same lab.

WORK COMPLETED

We have succeeded in creating two new organisms to add to our automaton zoo: a prototype head-down deposit-feeder and a fiddler crab, two common animals and bioturbators in nearshore/marsh sediments. We have also made significant progress towards a working lugworm, which also features prominently in near shore ecologies. (Huang and Reed, supervised by Boudreau)

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14. ABSTRACT
T he long term goal is a quantitative and mechanistic understanding of the relationship between infaunal ecology and the consequent modification of sediments, including the creation and destruction of heterogeneities and the modes and rates of sediment component mixing.

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In addition, we have continued to develop analytical models of bioturbation, in order to compare with the results from LABS. The prime theoretical question we considered in this work was the nature of the relationship between LABS and classical 1-D biodiffusion models of tracers. (Boudreau, Middelburg and Meysman)

RESULTS

1) *Automaton Results*. Figure 1(A&B) visualizes the behavior and effects of four head-down deposit-feeders in a typical nearshore sediment as simulated in LABS. Two layers of color tagged sediments have beed added to highlight the advective motions caused by the feeding action of these worms and the diffusion created by chance segegation and infilling of the burrows, i.e. a white layer between 0-1 cm depth and a black layer between 7-8 cm depth. The organisms do not disciminate tagged particles from untagged. The first figure shows the situation 4 hours into the simulation and the second is 25 days into the simulation. The parameter values, such as worm length and ingestion rate are taken fron Rice (1986, Jour. Marine Research).

The advection of the surface layer is best appreciated by considering the organism on the far left. In Fig. 1 A, surface-layer material with the lateral feeding range of the head (orange) is just beginning to descend to the feeding depth; in Fig. 1B, the surface layer material has just reached the feeding zone, when the organism dislocated to a new burrow location to the right. Immediately above this surface material is a dark patch with is obviously sediment that was originally in the feeding zone that has been defecated to the surface and tranlated by biological advection downward. However there is still white surface material above that dark material. Thus there is differential advection, and that leads to mixing , i.e., biodiffusion. The other burrows display similar phenomena.

Figure 2 illustrates the observed and predicted depth distributions of the isotope ^{7}Be in a New England sediment, as studied by Rice (1986). The LABS data is created by attaching a normalized amount of ^{7}Be to each particle that settles to the surface and laterally averaging the resulting 2-D distribution to get a mean depth profile of the isotope. Comparison between Figs 2A and 2B show that the profiles are similar, taking into account that the mean position of the LABS sediment-water is at a depth of 0.5 cm. (The scattered values above this depth are created by jutting surface roughness elements.)

Figure 3 compares the downward advective velocity created by head-down deposit feeding in situ (Fig. 3 A) and in LABS (Fig. 3B). The lines to compare are the line on the left in Fig. 3a and the blue (right-hand) line in Fig. 3B. Without adjusting any parameters, LABS quite accurately reproduces the advections calculated by Rice (1986). The only important parameter is the feeding rate, and that is fixed by observation and the ^{7}Be profile.

The other organism now complete is a fiddler crab. Figure 4 illustrates the crab and the mixing caused by its burrowing and the subsequent in-filling of the burrows, either by slumping of surface materials by collapse of the burrow. Surface material has again been color-tagged white to highlight the mixing. We have only begun to examine these affects and will report on them in the next fiscal year's report.
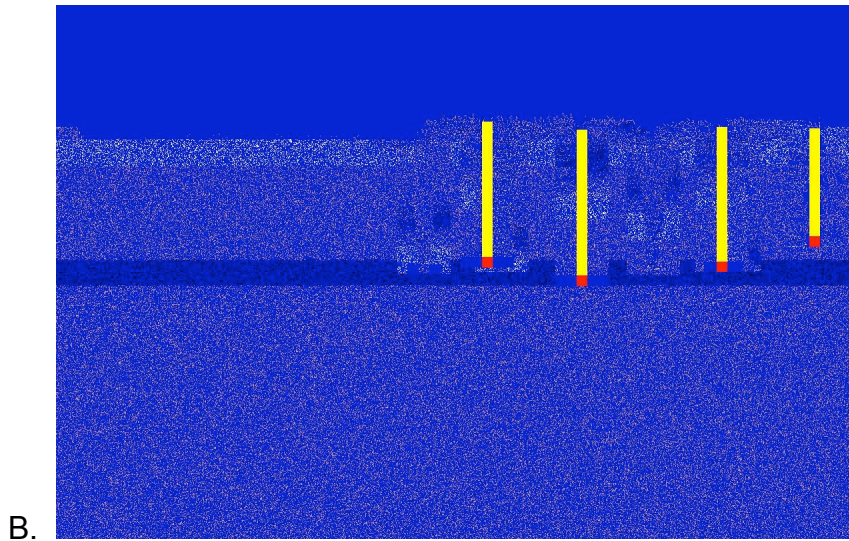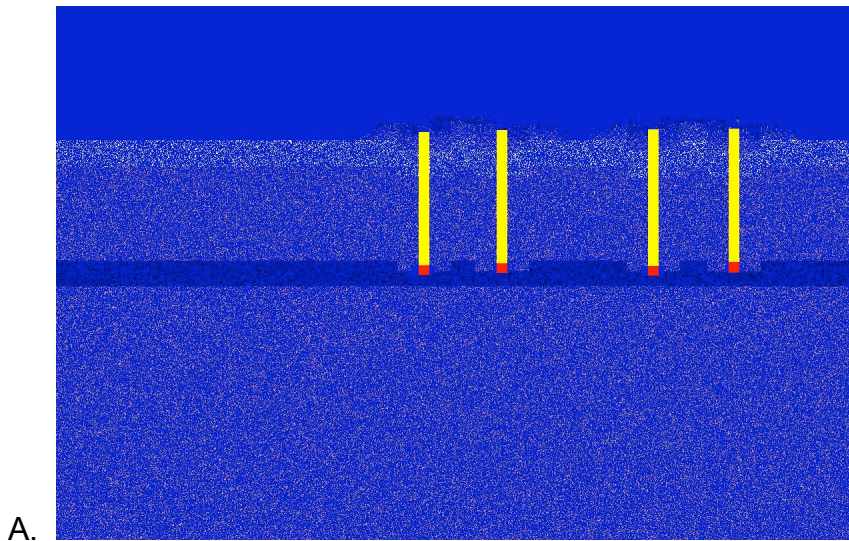
Figure 1. Visualization of head-down deposit-feeders and their effects on color-tagged particles. The worms are the yellow "structures" with the red head; they are about 8 cm in length and ½ cm across. The top figure (A) shows the initial conditions with black-colored particles in the feeding zone and white ones near the surface. The bottom figure (B) illustrates the conditions 25 days into the simulation. Biologically induced downward advection (displacements) and diffusion are now quite apparent.

A.   B.
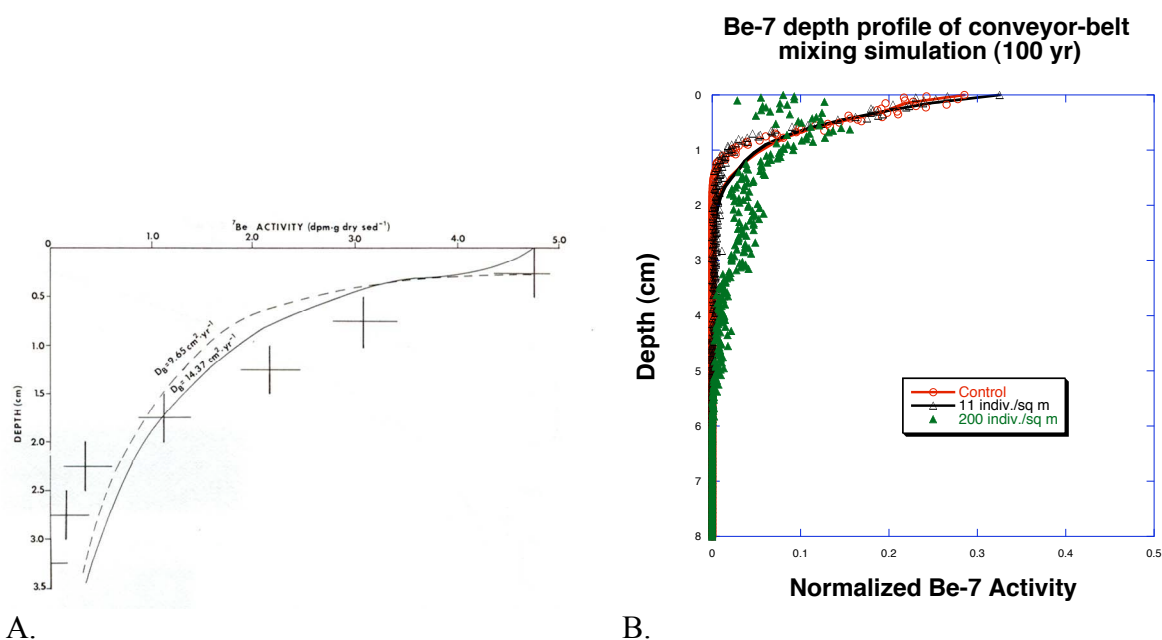
Figure 2. Diagram A. Plot of ^{7}Be in a New England sediment inhabited by head-down deposit-feeders, as measured by Rice (1986). Diagram B. Plot of the predicted ^{7}Be profiles by laterally averaging the sediment in the LABS model. The mean sediment-water interface is at 0.5 cm depth on this plot. The predicted activity of the tracer is similar to the observed.

A.   B.

Figure 3 Plots of the biologically-induced (mean) burial velocity, created by head-down deposit-feeding, at a marsh site in New England (Diagram A) and a equivalent simulation by LABS (Diagram B). The blue (right-hand) line in B is the prediction of the left-hand line in A, and the agreement is excellent.

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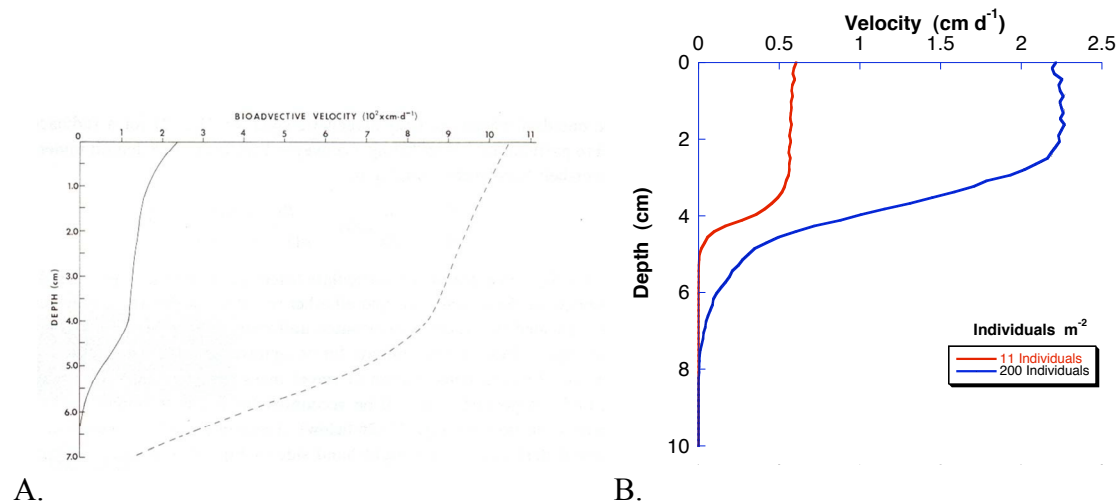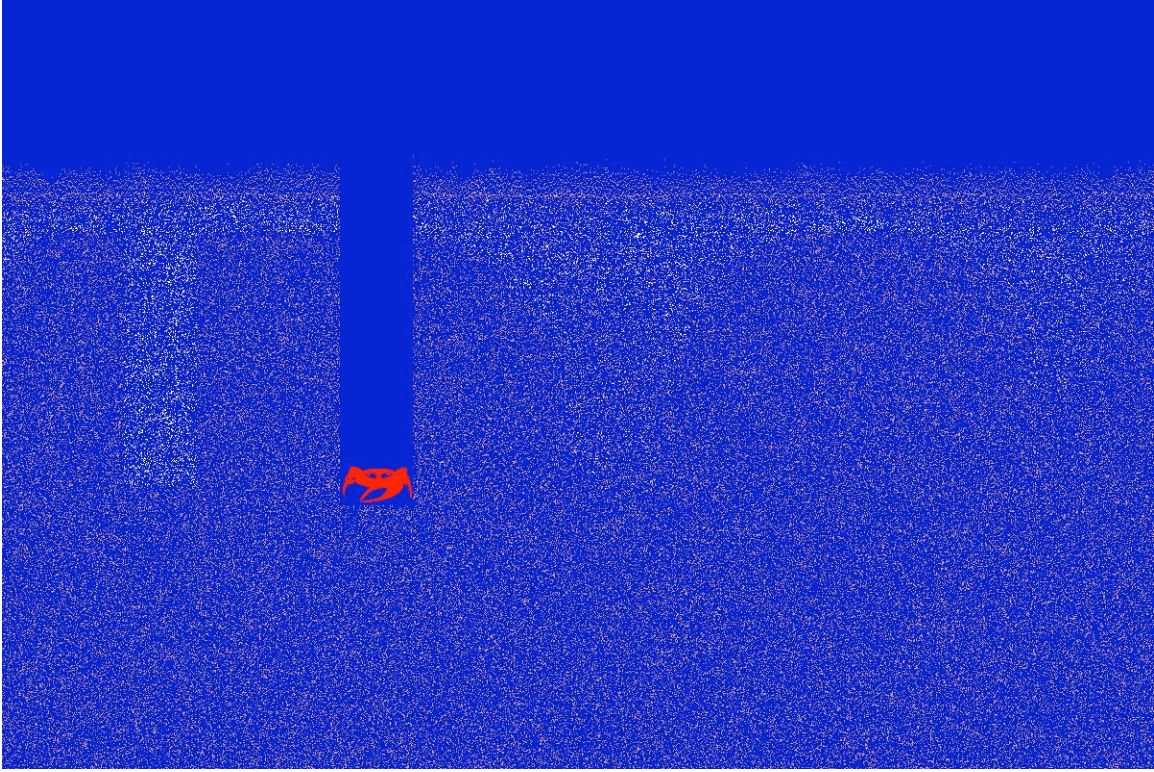*Figure 4. Visualization of a fiddle crab in LABS, its burrowing and the effects on white color-tagged particles, initially at the sediment-water interface. The crab(red) is about 4 cm in size and burrows to 12 cm. The in-filled burrow on the left was accomplished by filling it with surface naterials only; this produces a vertical column of tagged and untagged particles. The in-filled burrow to the right of the crab was filled in by collapse of the surrounding sediments, to produce a cone-like distribution of tagged and untagged particles.*

2) *Deterministic Modelling Results.* The current state of modelling bioturbation of sediments is one marked by confusion because of uncertainty in the treatment of porosity. This has lead to conflicting conservation equations for radiotracers, particularly when assuming steady-state compaction. We have re-examined this situation in the context of multi-phase, multi-component continuum theory. By considering the conservation of momentum, in addition to mass, we have identified the correct reference velocity to which biodiffusional fluxes should be scaled. We find that the total advective velocity can be decomposed into a physical part, determined by accumulation and compaction, and a superimposed biological part, resulting from bioturbation. From that, we have formulated a consistent set of model equations that govern (1) transient porosity and transient tracer concentrations, (2) steady-state porosity and transient tracer concentrations, and (3) steady-state porosity and steady-state tracer concentrations, in sediments that are subject to both compaction and bioturbation. Subsequently, these results were implemented for two specific end-member biodiffusion models: organism-induced motions cause bulk mixing of sediment with concurrent attenuation of porosity gradients (interphase mixing), or these motions simply intermix the solid components, leaving the porosity unchanged (intraphase mixing). Most importantly, we prove that under the assumption of steady-state compaction there exists only one correct form of the steady-state conservation equation for a radiotracer, regardless of the mode of biodiffusion, i.e.

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$$\frac{\partial}{\partial x}\left[\phi^s D_B \frac{\partial C_i^s}{\partial x}\right] - \frac{F_{sed}^s}{\rho^s}\frac{\partial C_i^s}{\partial x} - \phi^s \lambda_i C_i^s = 0$$

where x is depth, C_i^s is the concention/activity of the tracer, F_s is the constant flux of solid sediment to the sediment-water interface, ρ^s is the density of the solid phase, ϕ^s is the solid volume fraction, D_B is the biodiffusion coefficient, and λ is the decay constant. This resolves, once and for all time, the correct form of equation to model isotopes in natural sediments with a porosity gradient.   It also allows us to properly treat the results from LABS with variable porosity.

IMPACT/APPLICATIONS

Our results will prove to be highly significant to understanding of chemical movement in sediments and to acoustic seafloor imaging, i.e., studies of heterogeneity.

RELATED PROJECTS

We are working in collaboration with Peter Jumars (Univ. Maine), and his PhD student Kelley Dorgan, who are measuring animal locomotion rates and modes of movement. Their results will be used as inputs into our model.

PUBLICATIONS

Meysman, F., Boudreau, B.P. and Middelburg, J.J. (2005) Modelling reactive transport in sediments subject to bioturbation and compaction Geochimica et Cosmochimica Acta v. 69, 3601-3617.

Boudreau, B.P. (2005) Modelling Mixing and Diagenesis, in Kristensen, E., Kostka, J., and Haese, R.H., eds., *Macro- and microorganisms in marine sediment*, AGU Series "Coastal and Estuarine Studies" 60, 323-340.

Grigg, N.J., Boudreau, B.P., Webster, I.T., and Ford, P.W. (2005) The non-local model of porewater irrigation: limits to its equivalence with a cylinder diffusion model. Journal of Marine Research, v. 63, 437-455.